On Pair Content and Variability of Sub-Parsec Jets in Quasars

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ABSTRACT

X–ray observations of blazars associated with the OVV (Optically Violently Variable) quasars put strong constraints on the e^+e^- pair content of radio-loud quasar jets. From those observations, we infer that jets in quasars contain many more e^+e^- pairs than protons, but dynamically are still dominated by protons. In particular, we show that pure e^+e^- jet models can be excluded, as they overpredict soft X–ray radiation; likewise, pure proton-electron jets can be excluded, as they predict too weak nonthermal X–ray radiation. An intermediate case is viable. We demonstrate that jets which are initially proton-electron ("proto-jets") can be pair-loaded via interaction with 100 – 300 keV photons produced in hot accretion disc coronae, likely to exist in active galactic nuclei in general. If the coronal radiation is powered by magnetic flares, the pair loading is expected to be non-uniform and non-axisymmetric. Together with radiation drag, this leads to velocity and density perturbations in a jet and formation of shocks, where the pairs are accelerated. Such a scenario can explain rapid (time scale of $\sim$ a day) variability observed in OVV quasars.

Subject headings: galaxies: jets — plasmas — radiation mechanisms: non-thermal

1. INTRODUCTION

One of the basic unresolved questions regarding the nature of jets in radio loud quasars is that of their composition: are they made from protons and electrons, or electron-positron pairs, or from a mixture of both? Arguments in favor of proton-electron jets in quasars have been recently advanced by Celotti & Fabian (1993). Using synchrotron self-Compton constraints from radio-core observations and information about energetics of jets from radio-lobe studies, those authors showed that in the case of pure electron-positron jets the required number of e^+e^- pairs is too high to be delivered from the central engine. The limit is imposed by the annihilation process (Guilbert, Fabian, & Rees 1983).

On the other hand, the recently discovered circular polarization in the radio cores of the γ–ray bright OVV quasar 3C 279 and several other objects and its interpretation via the "Faraday conversion" process suggests that the jet plasma is dominated by e^+e^- pairs (Wardle et al. 1998; Wardle & Homan 1999). The fact that jets are likely to be pair dominated has also been inferred from synchrotron self-Compton analyses of compact radio components in radio galaxy M87 (Reynolds et al. 1996), and in quasar 3C 279 (Hirotani et al. 1999). In this paper we derive constraints imposed on the pair content of quasar jets by X–ray observations of OVV quasars, i.e. those radio loud quasars which are observed at very small angles to the jet axis, and often detected in the MeV - GeV γ–ray regime. Our results suggest that the pair content of quasar jets is high, but that dynamically the jets are dominated by protons.

The question of composition of the jet plasma is closely related to that of the formation of the jet. Jets can be launched as outflows dominated by Poynting flux, generated in the force-free magnetosphere of the black hole, or as hydromagnetic winds driven centrifugally from an accretion disc (see, e.g., a review by Lovelace et al. 1999). Electromagnetically dominated outflows are converted to pair dominated jets (Romanova & Lovelace 1997; Levinson 1998), whilst hydromagnetic winds give rise to proton-electron dominated jets (Blandford & Payne 1982). While the pair-dominated jets are predicted to be relativistic, the proton-electron jets can be either relativistic or non-relativistic, depending on whether the magnetic forces dominate over gravity in the accretion disc corona (Meier et al. 1997). In particular, relativistic hydromagnetic jets can be launched deeply in the ergosphere of fast-rotating black holes (Koide et al. 1999). If this is the case, and the surrounding accretion disc corona is as hot as inferred from the spectra of Seyfert galaxies (see, e.g., Zdziarski et al. 1994; Matt 1999), the proton-electron jets can be pair-loaded via the interactions with the coronal hard X–rays / soft γ–rays. We demonstrate that this process is efficient enough to provide the number of pairs required to account for the observed X–ray spectra of OVV quasars. Furthermore, the rapid X–ray variability of Seyferts (Green et al.

1993; Hayashida et al. 1998) indicates that the corona is likely to have dynamical character (as would be if it is powered by magnetic flares), and thus the hydromagnetic outflows are expected to be loaded by pairs nonuniformly and non-axisymmetrically. This, together with the radiation drag imposed by the coronal and disc radiation fields on pairs, can lead to a modulation of the velocity and density of the plasma in a jet, and therefore to production of shocks and acceleration of particles responsible for the variable nonthermal radiation.

Our paper is organized as follows: In §2 we demonstrate that pure pair jets overpredict the soft X–ray flux; in §3 we show that jets which are dynamically dominated by protons must be heavily pair-loaded in order to provide the observed nonthermal X–ray radiation; and in §4 we show that hydromagnetic outflows can be pair-loaded due to interaction with hard X–rays / soft γ–rays from the hot accretion disc corona. Our results are summarized in §5.

2. ELECTRON-POSITRON JETS

2.1. Cold pairs

If the relativistic jet is dynamically dominated by cold e^+e^- pairs, then the external UV photons will be Comptonized by those pairs and thus boosted in frequency by a square of a bulk Lorentz factor Γ and collimated along the jet axis. In this case, in addition to the nonthermal radiation from the jet – which results in the phenomenon called blazar – the observer located at $\theta_{obs} \leq 1/\Gamma$ should see a soft X–ray "bump" superimposed on the continuum in OVV quasars. Such spectral feature, predicted theoretically by Begelman & Sikora (1987), has not been observed, and this fact can be used to derive an upper limit for a pair content of quasar jets (Sikora et al. 1997).

Luminosity of the soft X–ray bump produced by the above "bulk-Compton" (BC) process is

$$L_{BC} \simeq \mathcal{A} \int_{r_0} \frac{1-e^{-\tau_j}}{\tau_j} \left| \frac{dE_e}{dt} \right| n_e \, dV, \tag{1}$$

where

$$\left| \frac{dE_e}{dt} \right| = m_e c^2 \left| \frac{d\Gamma}{dt} \right| = \frac{4}{3} c \sigma_T u_{diff} \Gamma^2 \, , \tag{2}$$

$$u_{diff} = \frac{\xi L_d}{4\pi r^2 c} \, , \tag{3}$$

$\mathcal{A}$ is the beaming amplification factor, L_d is the luminosity of an accretion disc, ξ is the fraction of the accretion disk which at the given distance r is isotropized due to rescattering

or reprocessing, n_e is the density of electrons plus positrons, $dV = \pi a^2 dr$, $\tau_j = n_e a \sigma_T$, a is the cross-section radius of a jet, and r_0 is the distance at which the jet is fully formed (accelerated and collimated).

Assuming that jet is conical and that at $r > r_0$ the electron/positron number flux is conserved (no pair production), we have $n_e \propto 1/r^2$, and $\tau_j = r_1/r$, where by r_1 we denote the distance at which $\tau_j = 1$. Then, for jets with a half-angle $\theta_j \equiv a/r \leq 1/\Gamma$, Eqs. (1)-(3) give

$$L_{BC} \simeq \frac{1}{3}(\Gamma\theta_j)(\xi L_d)\Gamma^3 \begin{cases} \ln\frac{r_1}{r_0} + 1 & \text{if } \tau_j(r_0) > 1 \\ \frac{r_1}{r_0} & \text{if } \tau_j(r_0) < 1 \end{cases} , \tag{4}$$

where we used $\mathcal{A} = \Gamma^2$. The value of r_1 depends on the electron/positron number flux, dN_e/dt, which – for energy flux in a jet L_j dominated by kinetic energy flux of cold pairs – is equal to $L_j/m_e c^2 \Gamma$. Noting that $dN_e/dt \simeq n_e c \pi a^2$, we obtain

$$r_1 = \frac{1}{\sigma_T n_e \theta_j} \simeq \frac{\sigma_T L_j}{\pi m_e c^3 \theta_j \Gamma} \simeq 10^{17} \frac{L_{j,46}}{\theta_j \Gamma} \, \mathrm{cm} \, , \tag{5}$$

If $r_0 > r_1$ then r_1 should be treated only as a formal parameter which provides normalization of τ_j. However, noting the very large value of r_1 one can expect that $r_0 < r_1$ and, therefore, the predicted Bulk-Compton luminosity is

$$L_{BC} > 3 \times 10^{47} (\Gamma\theta_j)(\xi L_d)_{45}(\Gamma/10)^3(\ln(r_1/r_0) + 1) \, \mathrm{erg\,s^{-1}} \, . \tag{6}$$

The BC spectral component peaks at $h\nu \sim \Gamma^2 h\nu_{UV} \simeq (\Gamma/10)^2$ keV, where typical luminosities observed in OVV quasars are $\sim 10^{46}$ erg s^{-1} (Sambruna 1997), while the spectra are consistent with simple power laws (cf. Kubo et al. 1998). Thus, one can conclude that *pure electron-positron jet models can be excluded as overpredicting soft X–ray radiation of OVV quasars.*

2.2. Relativistic "thermal" pairs

It is of course possible that because of inefficient cooling of electrons/positrons below a given energy, the multiple reacceleration process balances adiabatic losses in the conically diverging jet, and the pairs, once accelerated, remain relativistic forever. If the relativistic electrons are narrowly distributed around some $\bar{\gamma}$, then taking into account that $|dE_e/dt| \propto \Gamma^2 \bar{\gamma}^2$, $n_e \propto L_j/\bar{\gamma}$, and $r_1 \simeq r_1(\bar{\gamma} = 1)/\bar{\gamma}$, and assuming $r_0 > r_1$, the bulk-Compton luminosity would be

$$L_{BC} = 3 \times 10^{47} (\Gamma\theta_j)(\xi L_d)_{45}(\Gamma/10)^3 (r_1/r_0)\bar{\gamma} \simeq 3 \times 10^{48} \frac{(\xi L_d)_{45}(\Gamma/10)^3 L_{j,46}}{(r_0/10^{16}\mathrm{cm})} \, \mathrm{erg\,s^{-1}} \, , \tag{7}$$

and would peak at $\sim h\nu \simeq \Gamma^2 \bar{\gamma}^2 \nu_{UV} \simeq \bar{\gamma}^2 (\Gamma/10)^2$ keV. No such "bumps" have been detected at keV energies. Alternatively, one can speculate that the X–ray spectra of OVV quasars consist of superposed multiple "thermal" peaks produced over several decades of distance (cf. Sikora et al. 1997). In this case it may be possible to match the observed X–ray spectral slopes, but nonetheless, the model predicts too large luminosity.

3. PROTON-ELECTRON JETS

The other extreme would have no e^+e^- pairs in a jet. For a given energy flux in the jet, L_j, which now is proportional to $n_p m_p$, the number of electrons in a jet is m_e/m_p times smaller than the number of electrons plus positrons in the jet made from cold pairs. Thus, noting that $r_1(n_e = n_p) = (m_e/m_p) r_1(n_p = 0) \simeq 0.5 \times 10^{14}$ cm, one can find that the proton-electron jets do not overproduce the soft X–ray luminosities observed in OVV quasars, provided that $r_0 \geq 15\, r_1 \simeq 10^{15}$ cm.

However, such pure proton-electron jets are relatively inefficient in producing the nonthermal radiation, and this is for the same reason as above – low number of electrons. This is apparent from a study of the low energy tails of the nonthermal radiation components, where the requirement for the number of electrons is largest. In the case of synchrotron radiation, such tails are not observed because they are self-absorbed, and the only spectral band where the presence of the lower energy relativistic electrons can be evident are the soft and mid-energy X–rays, 0.1 – 20 keV.

It has been shown in many papers (see, e.g., Sikora, Begelman, & Rees 1994) that the γ–ray spectra observed by the EGRET instrument in OVV quasars are likely to be produced by Comptonization of external diffuse radiation field, via the so-called external radiation Compton (ERC) process. Can this process be also responsible for the X–ray spectra of OVV quasars? In the one zone model and for the narrow spectral distribution of the soft radiation field, the power law X–ray spectra are produced by electrons with energy distribution obeying $n'_\gamma = C_n \gamma^{-s}$, where $s = 2\alpha_X + 1$ (note that throughout this paper, all quantities except for γ are primed if measured in the frame co-moving with the jet). Assuming that at a distance r_{fl}, where the blazar phenomenon is produced, all available electrons are accelerated and that energy flux in the jet is dominated by cold protons, i.e., that

$$n'_e = \int_{\gamma_{min}} n'_\gamma d\gamma = n'_p \simeq \frac{L_j}{m_p c^3 \Gamma^2 \pi a^2}\,, \tag{8}$$

we obtain

$$C_n = \frac{(s-1)\,\gamma_{min}^{s-1}\,L_j}{m_p c^3 \pi\, a^2\, \Gamma^2}\,. \tag{9}$$

The ERC luminosity is then given by

$$(L_\nu \nu)_{ERC} \simeq \Gamma^4 (L'_{\nu'}\nu')_{ERC} \sim \Gamma^4 (\frac{1}{2} N_\gamma \gamma) m_e c^2 \left|\frac{d\gamma}{dt'}\right|_{ERC} \simeq$$

$$\simeq 2.4 \frac{\sigma_T}{m_p c^2} a u_{diff} L_j \Gamma^4 \alpha_X \gamma_{min}^{2\alpha_X} \gamma^{2(1-\alpha_X)} \, , \tag{10}$$

where

$$m_e c^2 \left|\frac{d\gamma}{dt'}\right|_{ERC} \simeq (16/9) c \sigma_T u_{diff} \Gamma^2 \gamma^2 \, , \tag{11}$$

$$N_\gamma \simeq \frac{4}{3} \pi a^3 n'_\gamma \, , \tag{12}$$

and

$$\nu \simeq (4/3) \Gamma^2 \gamma^2 \nu_{ext} \, . \tag{13}$$

The external radiation field in quasars, as seen in the jet frame at a distance

$$r_{fl} = \frac{a}{\theta_j} \simeq \frac{c t_{fl} \Gamma}{\theta_j} \simeq 2.6 \times 10^{17} \, \frac{(t_{fl}/1\,\mathrm{d})(\Gamma/10)^2}{(\theta_j \Gamma)} \, \mathrm{cm}, \tag{14}$$

where t_{fl} is the time scale of duration of flares observed in OVV quasars, is dominated by two components, broad emission lines and near infrared radiation from hot dust. The broad emission lines provide radiation field with $h\nu_{ext} \simeq 10$ eV and

$$u_{diff(BEL)} \simeq \frac{L_{BEL}}{4\pi r_{fl}^2 c} \sim 3.9 \times 10^{-2} \frac{L_{BEL,45} (\theta_j \Gamma)^2}{(t_{fl}/1\,\mathrm{d})^2 (\Gamma/10)^4} \, \mathrm{erg\,cm^{-3}} \, . \tag{15}$$

The spectrum of the infrared radiation from hot dust, on the other hand, peaks around $h\nu_{ext} = 3kT \sim 0.26(T/1000)$ eV, and at a distance $r_{fl} < r_{IR} = \sqrt{L_d / 4\pi \sigma_{SB} T^4}$, has energy density

$$u_{diff(IR)} \simeq \xi_{IR} \frac{4\sigma_{SB}}{c} T^4 \simeq 7.6 \times 10^{-3} \xi_{IR} \left(\frac{T}{1000\,\mathrm{K}}\right)^4 \, \mathrm{erg\,cm^{-3}} \, , \tag{16}$$

where T is the temperature of dust, σ_{SB} is the Stefan-Boltzman constant, and ξ_{IR} is the fraction of the central source covered by the innermost parts of a dusty molecular torus. For $\Gamma \sim 10$ and typical $1 - 20$ keV spectral index $\alpha_X \simeq 0.6$ (Kii et al. 1992; Kubo et al. 1998), Comptonization of broad emission lines gives

$$(L_\nu \nu)_{C(BEL)} \simeq 6.4 \times 10^{43} \frac{L_{BEL,45}}{(t_{fl}/1\,\mathrm{d})} \left(\frac{\mathrm{h}\nu}{1\ \mathrm{keV}}\right)^{0.4} \gamma_{min}^{1.2} L_{j,46} (\theta_j \Gamma) \, \mathrm{erg\,s^{-1}} \, , \tag{17}$$

while Comptonization of near infrared radiation gives

$$(L_\nu \nu)_{C(IR)} \simeq 5.1 \times 10^{42} \left(\frac{\xi_{IR}}{0.1}\right) \left(\frac{T_{IR}}{1000\,\mathrm{K}}\right)^4 \left(\frac{t_{fl}}{1\,\mathrm{d}}\right) \left(\frac{\mathrm{h}\nu}{1\,\mathrm{keV}}\right)^{0.4} \gamma_{min}^{1.2} L_{j,46} \, \mathrm{erg\,s^{-1}} \, . \tag{18}$$

Note that in the case of Comptonization of UV photons, radiation at 1 keV is produced by electrons which are only weakly relativistic, with $\gamma \sim 1$ (see Eq. 13) and therefore this implies that γ_{min} also needs to be ~ 1. In the case of Comptonization of near infrared radiation, $\gamma_{min} \leq 50/\Gamma$.

As one can see from Eqs. (17) and (18), *Comptonization of external radiation by relativistic electrons in the proton-electron jets gives 1 keV luminosities which are* $\sim 100/L_{j,46}$ *times smaller than observed.*

Let us now determine whether the observed X–ray luminosities can be produced by the pure proton-electron jets via the synchrotron self-Compton (SSC) process, in addition to the ERC process responsible for the hard γ–ray emission. Luminosity of the SSC radiation can be estimated using the formula

$$(L_\nu \nu)_{SSC} \simeq \Gamma^4 (L_{\nu'}\nu')_{SSC} \simeq \Gamma^4 (\frac{1}{2} N_\gamma \gamma) m_e c^2 \left|\frac{d\gamma}{dt'}\right|_{SSC} \simeq$$

$$\simeq \frac{2\sigma_T}{3\pi m_p c^3} \frac{L_{syn} L_j}{a\Gamma^2} \alpha_X \gamma_{min}^{2\alpha_X} \gamma^{2(1-\alpha_X)} \,, \tag{19}$$

where

$$\left|\frac{d\gamma}{dt'}\right|_{SSC} = \frac{4c\sigma_T}{3m_e c^2} u'_{syn} \gamma^2 \,, \tag{20}$$

$$u'_{syn} \simeq \frac{L_{syn}}{2\pi c a^2 \Gamma^4} \,, \tag{21}$$

and

$$\nu \simeq (4/3)\gamma^2 \nu_{syn,m} \,, \tag{22}$$

where $h\nu_{syn,m} \sim 0.1$ eV is the typical location of the synchrotron spectrum peak in OVV quasars (cf. Fossati et al. 1998).

As it is apparent from Eq. (22), production of 1keV radiation by SSC process involves electrons with $\gamma \sim 100$. Therefore, γ_{min} is not restricted to such low values as in the case of the ERC processes, and, in principle, for $\gamma_{min} \sim 100$, the SSC model can reproduce the observed soft X–ray luminosities:

$$(L_\nu \nu)_{SSC} \sim 7.3 \times 10^{45} \frac{L_{syn,47} L_{j,46}}{(t_{fl}/1d)(\theta\Gamma)} \left(\frac{\mathrm{h}\nu}{1\,\mathrm{keV}}\right)^{0.4} (\gamma_{min}/100)^{1.2}\,\mathrm{erg\,s^{-1}} \,, \tag{23}$$

where as before we used $\Gamma = 10$ and $\alpha_X = 0.6$. However, since the electrons which produce X–ray spectra via the SSC process have the same energy range as those electrons which produce γ–rays above 1 MeV, the spectral slopes of both should be similar. The observations show that this is not the case; the γ–ray spectra above 1 MeV are much

steeper than the X–ray spectra in the 1 – 20 keV range, typically by $\Delta\alpha \simeq 0.5$ (Pohl et al. 1997). This contradiction can be eliminated by assuming that most of the electrons are injected with $\gamma \geq 500$. The X–rays are then produced by electrons which reach energies appropriate for X–ray production ($100 < \gamma < 500$ for 1 – 25 keV) by radiative energy losses and the resulting slope is $\alpha_X \simeq 0.5$ (Ghisellini et al. 1998; Mukherjee et al. 1999).

Summarizing this section we conclude that:

- Production of hard X–ray spectra by ERC process requires $\gamma_{min} < 10$ and the pair to proton number ratio
$$\frac{n_{pairs}}{n_p} \sim 50\,\frac{L_{SX,46}}{L_{j,46}}. \qquad (24)$$
where $L_{SX} \sim 10^{46}$ erg s^{-1} is the typical luminosity observed in OVV quasars around 1 keV;
- Hard X–ray spectra can be produced by pure proton-electron jets via the SSC process, but this requires extremely high values of minimum electron injection energies.

4. PAIR PRODUCTION AND VARIABILITY

We propose a scenario where jets are launched as proton-electron outflows in the innermost parts of the accretion flow and are loaded by pairs due to interactions with hard X–rays / soft γ–rays produced in the hot accretion disc coronae. This can well occur via a two-step process. The first step is Compton boosting of coronal photons (with initial energy of 100 – 300 keV) up to few MeV by cold electrons in the outflow propagating through the central region (Begelman & Sikora 1987). Provided that luminosity of the coronal radiation at > 100 keV is $L_{s\gamma} \sim 10^{46}$ erg s^{-1}, as can be deduced from extrapolation of 2 – 10 keV spectra observed in non-OVV radio-loud quasars (see, e.g., Cappi et al. 1997; Xu et al. 1999), one can find that opacity for the above interactions is very high,

$$\tau_{e\gamma} \simeq n_x r_{corona} \sigma_T \sim 15 \frac{(L_{s\gamma}/10^{46}\mathrm{erg\,s^{-1}})}{(h\nu/200\,\mathrm{keV})(r_{corona}/3\times10^{15}\mathrm{cm})}. \qquad (25)$$

This means that each electron in the inner parts of the outflow (essentially forming a "proto-jet") produces on the order of 10 or more 1 – 3 MeV photons. The second step is the absorption of MeV photons by the coronal (100 – 300 keV) photons in the pair creation process. The pairs created in such a manner are dragged by the jet, but before leaving the compact coronal radiation field, they produce a second generation of MeV photons, and they in turn produce next generation of pairs. Such pair cascade can continue until the time when the proto-jet becomes opaque for coronal radiation, i.e., when $n_e r_{corona} \sigma_T \sim 1$. Within this limit, the electron/positron flux integrated over the cross-section of the proto-jet can

reach the value

$$\dot{N}_e \simeq n_e c \Omega_i r_{corona}^2 \simeq \frac{c\Omega_i r_{corona}}{\sigma_T}\,, \tag{26}$$

where Ω_i is the initial solid angle of the outflow. Comparing this electron/positron flux with the total proton flux

$$\dot{N}_p \sim \frac{L_j}{\Gamma m_p c^2}\,, \tag{27}$$

we find that proton-electron winds can be loaded by pairs in the central compact X–ray source up to the value

$$\frac{n_{pairs}}{n_p} \simeq \frac{\dot{N}_e/2}{\dot{N}_p} \simeq \frac{m_p c^3}{2\sigma_T}\frac{r_{corona}\Omega_i\Gamma}{L_j} \simeq 30\,\frac{r_{corona}}{3\times 10^{15}\mathrm{cm}}\,\frac{\Omega_i}{L_{j,46}}\,\frac{\Gamma}{3}\,. \tag{28}$$

This corresponds roughly to the pair content given by Eq. (24), provided that Ω_i is not very small. Note that a large initial opening angle of the central outflow is expected, as jets with $L_j \sim 10^{46}$ erg s^{-1} carry too much momentum to be effectively collimated by the innermost parts of the accretion disc corona. Due to radial quasi-expansion, the outflow is rapidly diluted and can be collimated to the narrow jet by disc winds at $r > 100$ gravitational radii (cf. Begelman 1995).

It should be mentioned here that loading of quasar jets by pairs via absorption of γ–rays produced within the jet by external radiation field has been also proposed by Blandford and Levinson (1995) (BL95). However, their scenario is very different from ours in many respects. In the BL95 model, both pairs and nonthermal radiation are produced over several decades of distance; in our model, pair production is taking place at the base of a jet, whereas nonthermal radiation is produced at distances $10^{17} - 10^{18}$ cm. The BL95 model involves relativistic electrons, and pairs are produced by absorption of nonthermal radiation extending up to GeV energies, while our pair loading scenario involves cold electrons (as measured in the jet comoving frame), and pairs are produced by absorption of photons with energy 1 – 3 MeV. In their scenario, Comptonization of the UV bump by relativistic pair cascades leads to a production of a power-law X–ray spectrum which is softer than that observed in OVV quasars; in our scenario — in the region where pairs are injected, i.e., at the base of a jet — the UV bump is Comptonized only by cold pairs, and this leads to a production of radiation only around $h\nu_{UV}(\Gamma/3)^2 \sim 100$ eV. Due to the wide opening angle of a jet at its base, this radiation is much less collimated than nonthermal radiation produced at larger distances, and therefore in OVV quasars, it may be relatively inconspicuous. The 100 eV excess can be detectable eventually in steep spectrum radio loud quasars, which have jets pointing further away from our line of sight. However, due to absorption by the ISM in the host, or our own Galaxy, this excess is predicted to be weak, and difficult to detect.

Another attractive feature of our model is that the pair loading of a jet via interactions of the proto-jet with the hard X–rays / soft γ–rays produced by accretion disk coronae can be responsible for fast ($\sim$ day) variability observed in OVV quasars. We know from observations that the (presumably isotropic) X–ray emission from Seyfert galaxies – and thus, by analogy, the non-jet, isotropic component in radio loud quasars – is rapidly variable (although in OVV quasars, this component is "swamped" by stronger, relativistically boosted flux). This suggests that the corona is likely to have dynamical character: it may be powered by magnetic flares, or else by a possible instability of the innermost region of the accretion disk. In either case, the jet is expected to be loaded by pairs non-uniformly and non-axisymmetrically. The patches of the local pair excesses in a jet suffer large radiation drag (Sikora et al. 1996) and are forced to move slower than the surrounding gas. Therefore, they provide natural sites for shock formation and particle acceleration.

While the above mechanism is viable as an explanation of rapid X–ray and γ–ray variability observed in OVV quasars, we note that pair density variations, as modulated by magnetic flares in the disk, are too rapid to produce variability of the *radio* flux. The long-term (months to years) variability in OVV quasars observed in all spectral bands including radio, are more likely to result from modulation of the variable flux of protons. Such modulation can be induced by the variability of the accretion rate in the inner parts of the accretion disc. The observed long term optical variability in both radio-loud and radio-quiet quasars supports this view (see, e.g., Giveon et al. 1999 and references therein).

5. SUMMARY

- Models of quasar jets consisting purely of e^+e^- pairs can be excluded because they predict much larger soft X–ray luminosities than observed in OVV quasars. On the other hand, models with jets consisting solely of proton-electron plasma jets are excluded, as they predict much weaker nonthermal X–ray radiation than observed in OVV quasars. Spectra of nonthermal flares in those objects *can* be explained in terms of a simple homogeneous ERC model, provided that the number of pairs per proton reaches values $\sim 50\,(L_{SX}/L_j)$.
- We suggest that initially, jets consist mainly of proton-electron plasma (where the protons provide the inertia to account for the kinetic luminosity of the jet), and subsequently are loaded by e^+e^- pairs by interactions with hard X–rays / soft γ–rays from hot accretion disc coronae. This requires that the coronal temperatures reach values $\sim$ 100 keV, which are consistent with observations of Seyfert galaxies, with spectra uncontaminated by relativistic jets.
- Non-steady and non-axisymmetric pair loading of jets by X–rays from magnetic flares in the corona can be responsible for short term ($\sim$ day) variability observed in OVV

quasars. It should be emphasized here that alternative mechanisms of variability, such as modulation of the total energy flux in a jet by accretion rate or precession of a jet (cf. Gopal-Krishna & Wiita 1992) cannot operate on such short time scales. The lack of rapid (time scale of $\sim$ day), high amplitude variability in the UV band of radio lobe dominated quasars supports this view.

- The dissipative sites in quasar jets, where electrons/positrons are accelerated and produce nonthermal flares observed in OVV quasars, can be provided by shocks produced by collisions between inhomogeneities induced by non-uniform pair loading of the proto-jets. These shocks (and therefore particle acceleration) can be amplified eventually at a distance 0.1 – 1 pc due to reconfinement of a jet by the external gas pressure (Komissarov & Falle 1997; Nartallo et al. 1998).

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REFERENCES

Begelman, M.C. 1995, Proc. Natl. Acad. Sci. USA, 92, 11442

Begelman, M.C., & Sikora, M. 1987, ApJ, 322, 650

Blandford, R.D., & Levinson, A. 1995, ApJ, 441, 79

Blandford, R.D., & Payne, D.G. 1982, MNRAS, 199, 883

Cappi, M., Matsuoka, M., Comastri, A., Brinkmann, W., Elvis, M., Palumbo, G.G.C., & Vignali, C. 1997, ApJ, 478, 492

Celotti, A., & Fabian, A.C. 1993, MNRAS, 264, 228

Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433

Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451

Giveon, U., Maoz, D., Kaspi, S., Netzer, H., & Smith, P.S. 1999, MNRAS, 306, 637

Gopal-Krishna, & Wiita, P.J. 1992, A&A, 259, 109

Green, A.R., McHardy, I.M.M., & Lehto, H.J. 1993, MNRAS, 265, 664

Guilbert, P.W., Fabian, A.C., & Rees, M.J. 1983, MNRAS, 205, 593

Hayashida, K., Miyamoto, S., Kitamoto, S., & Negoro, H. 1998, ApJ, 500, 642

Hirotani, K., Iguchi, S., Kimura, M., & Wajima, K. 1999, PASJ, 51, 263

Kii, T., et al. 1992, in Frontiers of X–ray Astronomy, ed. Y. Tanaka & K. Koyama (Tokyo: Universal Academy Press), 577

Koide, S., Meier, D., Shibata, K., & Kudoh, T. 1999, ApJL, submitted (astrop-ph/9907435)

Komissarov, S.S., & Falle, S.A.E.G. 1997, MNRAS, 288, 833

Kubo, H., Takahashi, T., Madejski, G., Tashiro, M., Makino, F., Inoue, S., & Takahara, F. 1998, ApJ, 504, 693

Levinson, A. 1998, ApJ, 507, 145

Lovelace, R.V.E., Ustyugova, G.V., & Koldoba, A. V. 1999, preprint (astro-ph/9901256)

Matt, G. 1999, presented at "X–ray Astronomy", September 6-10, 1999, Bologna, Italy

Meier, D.L., Edgington, S., Godon, P., Payne, D.G., & Lind, K.R. 1997, Nature, 388, 350

Mukherjee, R., Böttcher, M., Hartman, R.C., Sreekumar, P., Thompson, D.J., Mahoney, W.A., Pursimo, T., Sillanpää, A., & Takalo, L.O. 1999, ApJ, in press (astro-ph/9901106)

Nartallo, R., Gear, W.K., Murray, A.G., Robson, E.I., & Hough, J.H. 1998, MNRAS, 297, 667

Pohl, M., Hartman, R.C., Jones, B.B., & Sreekumar, P. 1997, A&A, 326, 51

Reynolds, C.S., Fabian, A.C., Celotti, A., & Rees, M.J. 1996, MNRAS, 283, 873

Romanova, M.M., & Lovelace, R.V.E. 1997, ApJ, 475, 97

Sambruna, R.M. 1997, ApJ, 487, 536

Sikora, M., Begelman, M.C., & Rees, M.J. 1994, ApJ, 421, 153

Sikora, M., Sol, H., Begelman, M.C., & Madejski, G. 1996, MNRAS, 280, 781

Sikora, M., Madejski, G., Moderski, R., & Poutanen, J. 1997, ApJ, 484, 108

Wardle, J.F.C., & Homan, D.C. 1999, AAS Meeting 194

Wardle, J.F.C., Homan, D.C., Ojha, R., & Roberts, D. 1998, Nature, 395, 457

Xu, C., Livio, M., & Baum, S. 1999, AJ, 118, 1169

Zdziarski, A., Fabian, A., Nandra, K., Celotti, A. Rees, M., Done, C., Coppi, P., & Madejski, G. 1994, MNRAS, 269, L55

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